CAPTURE OF MAXIMUM WIND ENERGY FOR CONSTANT FREQUENCY OFF SHORE WIND FARM USING NOVEL CAPRA OPTIMIZATION ALGORITHM

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***Abstract*:** *This paper proposes that in wind power system design a powerful optimization technique can successfully maximize energy capture at given site, thus proposes a Novel Capra Optimization Algorithm (NCOA). Maximizing wind energy capture NCOA employ most common Constant frequency (CF) scheme as an alternative of using Variable frequency (VF) scheme. Since VF has the main drawback in controlling independently the speed of each turbine. Hence this paper proposes NCOA make an effort to enhance CF scheme for capturing maximum wind energy. NCOA is to evaluate for different wind speed scenarios applied to a standard case studies of constant electrical frequency off shore wind farm. The case study considers a wind farm composed of single turbine and four wind turbines based on synchronous generator. The simulation shows a significant enhancement of CF scheme 20% more than the VF scheme using NCOA and 94% percent of capture of total available wind power.*

Key words: *Capra Optimization, Maximum Energy capture, Maximum Wind power generation, optimal power coefficient.*

1. Introduction

Recent decade wind power generation system are receiving a lot of interest for the reason that they are cost viable, environmentally clean and safe renewable power sources, contrast to fossil fuel and nuclear power generation. Electric energy is produced from wind by means of a wind turbine and an electric generator. The generated electrical energy can be utilized either for separate loads or fed into the power grid through a suitable power electronic interfaces.

Various kind of electric generators are utilized for the generation of electric energy from wind such as squirrel cage induction generator (SCIG), the doubly fed induction generator (DFIG), and the synchronous generator (SG) [1]–[3].

In this proposed work SG is used because it offers of quite a lot of benefit in economical, low maintenance cost, and moreover easy to control [1]–[3]. Traditionally, the extracted energy from wind is converted into electric energy by using an SCIG or DFIG and is supplied to the grid or a standalone load. The main disadvantage of this arrangement is its poor efficiency because it does not track the capturing the maximum power [4], [5] as the wind velocity changes.

Numerous maximum power capturing methods have been employed such as most popular fuzzy logic-based, perturb-observe (PO) methods, anemometer-based (AM) method, calculation-based method [6]–[11], all these methods has drawbacks which are PO method has the turbine speed is varied in small steps, AM method has the cost of system increases because of anemometer is expensive, fuzzy based scheme is good but is difficult to put into practice [7] An intelligent maximum power extraction algorithm [11] consequences in slow maximum power capturing.

Capturing maximum power from wind alternate way of approach is to have suitable generators with power converters is used. SCIG with power converter [12]–[14] or DFIG is used; however, this frequency may be different from the grid. Hence, a power converter is needed to interface the induction generator to the grid [15].

In this paper proposes a novel optimization NCOA to capture maximum power generation from wind energy, NCOA proves to be more rapid than the most of the past schemes. The algorithm works in optimizing the power coefficient for constant wind velocity and variable wind velocity of CF scheme. The rest of this paper is organized as follows section 2 contains formation of wind turbine power generation. Section 3 provides the proposed NCOA formation. Section 4 Case studied is presented with two test cases of single wind power generation for CF scheme of various wind speed scenario and four wind power generation to enhance the CF scheme to capture maximum power generation from off shore wind form and compared with previous method in literature. Section 5 concludes the paper.

2. Wind Power Generation

The generated power from the wind turbine is given as [16];

$$P_w = \frac{1}{2} C_p \rho A v_w^3 \qquad (1)$$

Where

P_w Power generated from wind turbine

C_p Power Coefficient

v_w Average wind speed

A Surface covered by the wind wheel

ρ Air density

Power coefficient of the wind turbine can be articulated as [17],[18].

$$C_p(\lambda, \theta_{pitch}) = c_1\left(c_2 \frac{1}{\wedge} - c_3\theta_{pitch} - c_4\theta_{pitch}^{c_5} - c_6\right)e^{-c_7\frac{1}{\wedge}} \qquad (2)$$

$$\lambda = \frac{\omega R}{v_w} \qquad (3)$$

$$\frac{1}{\wedge} = \frac{1}{\lambda + c_8\theta_{pitch}} - \frac{c_9}{1+\theta_{pitch}^3} \qquad (4)$$

Where

θ_{pitch} Pitch angle

λ Tip speed ratio

$[c_1..c_9]$ Characteristic constant for each wind turbine

R length of the blade

ω Turbine speed in rad/sec

The optimum operating point of the wind turbine is the maximum value $C_p - \lambda$ curve. The maximum point of can be withstand when the wind speed should not cross the maximum threshold value, Hence the maximum C_p can be expressed as [16],

$$C_{P\max}(\lambda_{Cp\max}) = \left(\frac{c_1 c_2}{c_7}\right)e^{-\frac{c_6 c_7}{c_2}-1} \qquad (5)$$

The capturing of maximum power of wind turbine is function of power coefficient, tip speed ratio, wind speed velocity. The power coefficient is termed as the ratio of turbine power to wind power, which is the function of the tip speed ration as well as the blade pitch angle. λ is defined as the ratio of turbine speed at the tip of a blade to wind velocity

Typical single wind turbine (SWT) the $C_{p\max} - \lambda$ can be drawn and shown in the Fig. 1.

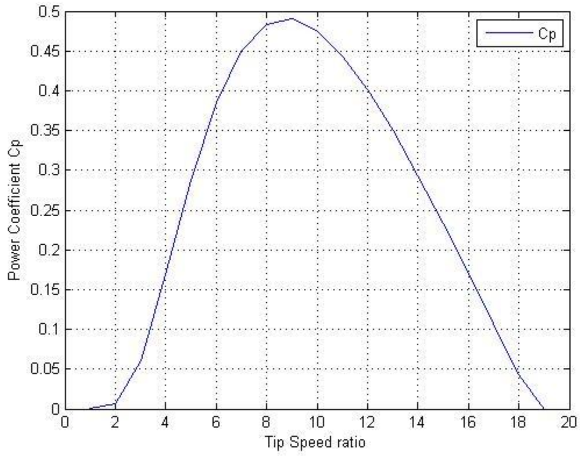

Fig 1. $C_{p\max} - \lambda$ curve

2.1 Capturing of Maximum Wind Power (CMWP)

Without loss of generosity, n number of wind turbine in a off shore wind farm with constant frequency can be expressed as according to [16],

$$\sum_{j=1}^{nw} P_w = \frac{1}{2}\rho A \sum_{i=1}^{nw} C_{pi} v_w^3 \qquad (6)$$

Where

nw Number of wind generators in a typical wind farm

C_{pi} Power Coefficient of j^{th} wind turbine

v_w Wind speed in m/sec

According to [16] the power coefficient C_{pi} can be evaluated as the pitch angle is assumed to 0, C_{pi} is computed using the Eq. (2). For all simulation in this paper the power coefficient of a typical single wind turbine is considered as same,

$$C_{pi}(\lambda) = 0.44\left(125\frac{1}{\lambda} + 0.002 - 6.94\right)e^{-16.5\left(\frac{1}{\lambda}+0.002\right)} \tag{7}$$

v_w Wind speed is obtained as random generation of Weibull probability distribution [16].

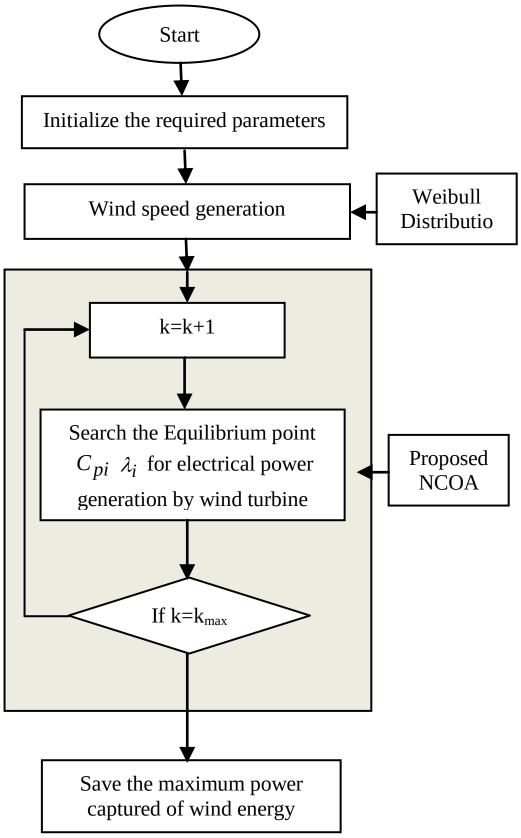

Fig 2. Proposed maximum power capturing evaluation procedure using NCOA.

3. Novel Capra Optimization

An herbivore genus known as Capra refers to domesticated goat's grazing behavior is modeled as optimizing algorithm to solve ED problems. An herbivore is an animal anatomically a physically adopted to eating a plant materials for their diet [19]. Herbivora is derived from Latin word "Herba" meaning a small plant and "vora" means to devour (eat). Herbivores employ numerous types of feeding strategies such as grazing and browsing [19]. Browsing means eating leafs, shoots and twins of shrubs and trees. Grazing refer to feed on growing grass and pasturage or to small portion of food [20].

The searching difference between the grazing and browsing behavior of the herbivores makes to choose the grazing behavior of herbivores namely Capra. Moreover Capra possesses a unique characteristic which separates them from other livestock. Capra is more capable of utilizing natural grazing land. Capra are able to cover wide area in search of grazing land [21] this motivates us to model the novel search algorithm.

The novel search algorithm namely Capra optimization algorithms are modeled as follows,

Capra is very forages, able to cover a wide area in search of grazing land. Capra's small mouth and split upper lips enable them to pick small leaves. Thus Capra finding the most nutritious available feed from the grazing land. The total optimal grassing intake of the Capra is modeled as [22],

$$ƛ_i = \beta_i * l_i \tag{8}$$

$ƛ_i$ Total optimal grass intake of the i^{th} Capra

β_i Bite rate of the i^{th} Capra

l_i Reachable grazing area of i^{th} Capra

Total optimal grassing intake $ƛ_i$ of Capra is depends upon the bite rate β_i and reachable grazing area l_i the reachable grazing area is modeled as,

$$l_i = rand(0\, to\, r(\chi(\psi))) \tag{9}$$

χ Grazing land type,

ψ Grazing Area

r Radius of the grazing area ψ

l Reachable area of Capra

3.1 Grazing land

Grazing land of a Capra plays an important role in optimizing the total intake of optimal grazing in the search space. Grazing land χ of Capra can be as mountain, grassland, health land, Machair, Rough pasture, Savanna, Steppe, Veld, Potrero (landform), Rangeland, etc.,

Choosing a proper grazing land χ leads to reduce the grazing area of Capra and increasing the optimization process. Hence choosing a proper grazing land is most vital for optimization. In this modeling, grazing land of Capra is assumed as $\chi = 1$ as unit circle of searching area. Length of the grazing area of the Capra is the next vital part of NCOA towards the optimal solution so the calculation of r is modeled in section 3.2.

3.2 Modeling of length grazing area

Consider a fenced circular grazing land χ with known radius R. At the edge of this grazing land χ is a pole with a rope attached to it. At the other end of the rope a Capra has been tied and what length of rope is necessary if we want the Capra to graze over exactly half the area of the grazing land? The above situation is described in the Fig 3.

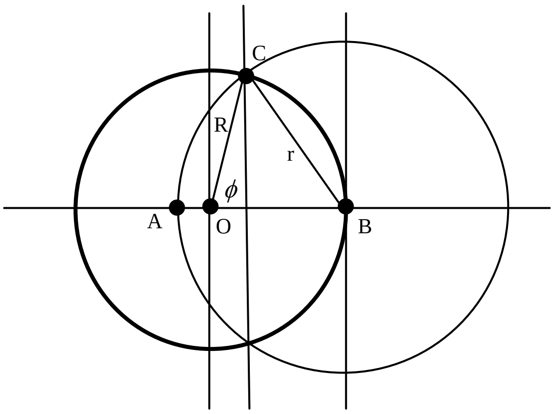

Fig 3. Grazing area of Capra

Fig 3. Describe the grazing land is represented by the circle of radius R through B centered at O, and the rope is attached to the fence at point B. The limit of the Capra's tether is the circle of radius r through C centered at B. The upper half of the section accessible by the Capra consists of a portion of the circle of radius r subtended by the angle θ, plus a portion of a unit circle subtended by the angle ϕ, minus the triangular region OCB.

Consider a typical reachable area of Capra is equal to some specified fraction ψ (such as one half) of the area of the upper half of the grazing land χ (i.e., the upper half of the unit circle χ =1). Thus we have

$$\frac{\theta}{2\pi}\left(\pi r^2\right)+\frac{\phi}{2\pi}\left(\pi\right)-\frac{y}{2}=\frac{\psi\pi}{2} \tag{10}$$

Multiplying through by 2 and simplifying,

$$\theta r^2+\phi-y=\psi\pi \tag{11}$$

Since CB is an arc of the circle centered at O, the angle OCB equals the angle OBC, and so $\theta=\left(\pi-\phi\right)/2$. Also, from the relations $r^2=(1-x)^2+y^2$, $y^2=1-x^2$ and $r^2=2(1-x)$ using these facts, the above equation can be written in the form

$$2(1-x)\left(\frac{\pi-\phi}{2}\right)+\phi-y=\psi\pi \tag{12}$$

Rearranging terms and making the substitutions $x=\cos(\phi)$ and $y=\sin(\phi)$ furthermore, if we set $\alpha=\pi-\phi$, and note that $\sin(\pi-\phi)=\sin(\phi)$ and $\cos(\pi-\phi)=-\cos(\phi)$ this equation can be written as

$$\sin(\alpha)-\alpha\cos(\alpha)=(1-\psi)\pi \tag{13}$$

Given any fraction ψ (the fraction of the circular grazing land reachable by the Capra), we can solve this equation (19) for the angle α, and then the length of the rope for Capra (length of the grazing area) is can be written as

$$r(\chi)=\sqrt{2(1+\cos(\alpha))} \tag{14}$$

3.3 Bite Count

In the behavior of herbivorous the bite count also had been an important factor for optimal grazing intake. In study Capra has been restricted to nominal 100-150 bites in order to minimize overlapping bites and the time that belonging between the first and the last bite has been recorded [23]. From the recordings the bite number, bite rate, bite strength, bite depth, bite area, bite volume are calculated using the following formula [23].

$$\beta_i=\frac{Bite\ Count}{Time\ spent\ in\ Biting} * per\ \min. \tag{15}$$

Obvious that the NCOA algorithm has the following control factors: 1) the grazing land of the Capra 2) the maximum and minimum limit of search space of an optimization problem, which is the grazing surface of the Capra 3) the maximum rotation for the optimization termed with respect to the bite count of the Capra. Updating these three parameters towards the most effective values has a higher probability of success than in other competing meta-heuristic methods. The implementation of NCOA to Capturing wind maximum power of wind generator in a typical wind farm as follows.

3.4 Implementation of NCOACMWP

3.4.1 Reachable grazing area of NCOACMWP

The reachable area of NCOACMW from Eq. no (9) is termed as $l_{\lambda i}$, which is determined by

$$l_{\lambda i} = rand(0\, to\, r(\chi(\psi))) \tag{16}$$

Selecting a fraction $\psi \in [0,1]$ (the fraction of the circular grazing land reachable by the Capra) and $\chi = 1$ as unit circle, Therefore by solving the following equation, the length of the grazing area has been calculated for generating the initial population for NCOACMW problem.

$$r_{\lambda}(\chi) = \sqrt{2(1+\cos(\alpha))} \tag{17}$$

3.4.2 Generation of initial population

Initialization of i^{th} individual population λ lambda as a function of Cp is key step of NCOACMWP formulated as,

$$\lambda_{ij} = \lambda_{ij}^{\max} * l_{\lambda i} \tag{18}$$

λ_{ij} Is the randomly generated tip speed ratio of the j^{th} wind turbine generator in i^{th} population and $l_{\lambda i}$ is a random number in the range of 0 - $r_{\lambda}(\chi)$. Repeat Eq. (18) i times to create the i uniformly distributed individuals as initial feasible solutions in the search space. The resultant gives the initial population as

$$\lambda_{ij} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \cdots & \lambda_{1j} \\ \lambda_{21} & \lambda_{22} & \cdots & \cdots & \lambda_{2j} \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \lambda_{i1} & \lambda_{i2} & \cdots & \cdots & \lambda_{ij} \end{bmatrix} \tag{19}$$

3.4.3 Calculate the power coefficient and objective function

Power coefficient Cp of all the generated individuals of Eq. (19) is calculated using Eq. no (7). Calculated individuals of Cp are evaluated with the objective function using Eq. no (6). All individual in the population is compared and ranked against all other individuals, then the objective value of chosen individual quantifies as the best optimum solution $Pwbest_{ij}$.

3.4.4 Optimal solution: grassing intakes

Optimal solution of NCOACMWP is obtained from grassing intake of the Capra bite count strategies applied to the $Pbest_{ij}$ of all i individuals as,

$$\lambda_{ij}^{new} = \lambda_{best_{ij}} + \tilde{\lambda}_{\lambda i} \tag{20}$$

$$\tilde{\lambda}_{\lambda i} = \beta_i * l_{\lambda i} \tag{21}$$

Where $\tilde{\lambda}_{\lambda i}$ is the optimal intake of the Capra from Eq. no (21) λ_{ij}^{new} The randomly generated tip speed ratio for the j^{th} wind generator in i^{th} population $\tilde{\lambda}_{\lambda i}$ is a random number in the range of 0 - $r_{\lambda}(\chi)$ and random bite count of 0 to 150 β_i [23] of percentage of byte count. $Pwbest_{ij}$. Best optimum solution for the current bite count is obtained for all individual in the population is compared and ranked against all other individuals.

3.4.5 Stopping criterion

The algorithm stops when the specific grazing count is reached.

3.5 Algorithm NCOACMWP

Step 1:Read the required initial data of j^{th} wind generator, pitch angle, scale factor, shape factor, cut-in speed, cut-off speed, radius of the blade, air density, number of poles, blade sweep area, rated power, number of generator n, population size i, number of grazing count $k_{\max}$, grazing land χ, Grazing area ψ, Bite count β_i

Step 2: Reachable Grazing

Step3: Evaluate the objective for each individual of power coefficient λ_{ij} using Eq. (6)

Step 4: Select the best individuals of $Pwbest_{ij}$ from step 4.

Step5: Generate λ_{ij}^{new} randomly selected mutually different integers that are different from the initial population index using Eq. (20) and Eq. (21)

Step 6: Chose the best vector compared with $Pwbest_{ij}$ initial vector versus best vector of $Pwbest_{ij}^{new}$

Step 7: If the $Pwbest_{ij}^{new}$ is the best individual vector k^{th} grazing count, repeat the step 5 to step 7 else go to step 9.

Step 8: Update the individual bite count β_i and repeat the step 5 to step 9 is repeated till the stopping criterion grazing count $k_{\max}$ is met.

4. Case Studies

The proposed work consider an off shore wind farm based on synchronous generator (SG). Reason behind for considering synchronous generator is compared to induction generator based on wind form is SG which rotates at equal mechanical speed. Therefore all wind turbines will rotate at same speed. Constant frequency off shore wind farm is considered because of various problems related to designing a variable frequency off shore farm such as stability, reactive power control. Due to these reasons the variable frequency farms are not considered.

The NCOACMWP is applied with the following test case. Test case employs to capture maximum wind energy by applying the methodology NCOA for single wind turbine for constant frequency of wind.

4.1 Parameter of wind turbine

The parameters related with wind turbine are taken form [16]. Pitch angle is considered as 0, generation of wind speed is from Weibull distribution with scale factor 6, shape factor 2, cut-in speed as 2.5 m/s, the cut-off speed 15 m/s. the radius of the wind turbine is 30m. Multiplication factor of gear box is considered as 60. The air density taken as $\rho = 1.225 kgm^{-3}$ and the rating of the SG have four poles, 2MW as rated power, 960 V as nominal voltage, 150kv as HVDC voltage. The power transformers are 2.5MVA rated. The wind farm transformers are rated at 10MVA.

4.2 Single turbine wind analysis

According to [24, 25], for a single wind turbine it is enough to guarantee maximum wind power generation by finding optimal power coefficient. Without loss of generosity of the wind turbines the simulation is carried out to capture maximum wind energy for the off shore wind farm having constant frequency. The result shows that the maximum power can be captured by NCOA. The statement is confirmed by analyzing Fig 4.

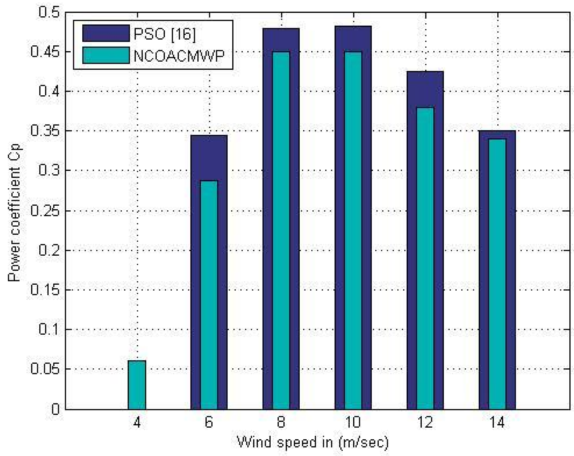

Fig 4. Optimal simulations by proposed NCOACMWP, wind speed vs. power coefficient

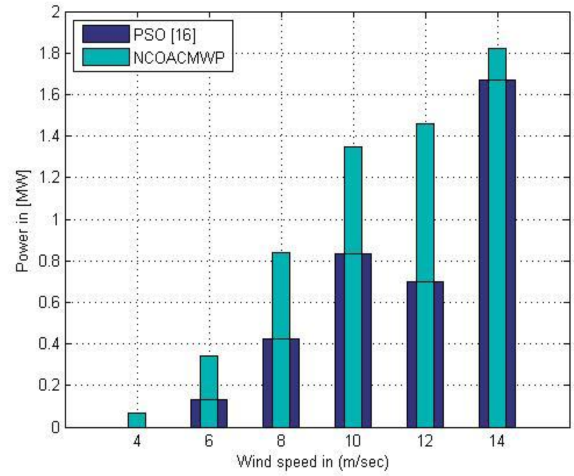

Fig 5. Optimal simulations by proposed NCOACMWP, wind speed vs. generated power output of single wind turbine

Fig 4 illustrates the optimal value of power coefficient Cp which yields the corresponding power captured by wind turbine. Fig 5 shows the simulated power captured by NCOACMWP for different wind power scenario according to [16]. According to [16] for the wind speed of 4m/s, 6m/s, 10m/s, 12m/s, 14m/s of Weibull distribution the simulation is carried out for 2MW rated wind power generator. Fig 5 represents for 4m/s the power captured is 0.067MW, 6m/s the power captured is 0.341MW, 8m/s the power captured is 0.838MW, 10m/s power captured is 1.346MW, 12m/s power captured is 1.46MW, and 14m/s the power captured is 1.82MW, which is greater than the well known algorithm, in literature.

Table1. Maximum power captured by NCOACMWP, Rated power 2MW

Wind speed m/sec	PSO [16] Pw in MW	PSO [16] % of wind power capture	NCOACMWP Pw in MW	NCOACMWP % of wind power capture
4	0.000	0.00	0.067	03.35
6	0.129	6.45	0.341	17.05
8	0.420	21.00	0.838	41.90
10	0.832	41.60	1.346	67.30
12	1.270	63.50	1.460	73.00
14	1.670	83.50	1.820	94.0

Table I represents the maximum power captured by using NCOACMWP algorithm with the analysis of different wind speeds generated randomly by a Weibull distribution for off shore wind farms. It clearly shows how the power capture is substantially incremented by NCOACMWP when compared to PSO [16]. Also the percentage of capturing wind energy is improved from 83.5% to 94.0% for the 2MW rated wind generator using proposed NCOACMWP for constant frequency. Repeating this analysis for all the wind scenarios, a maximum power capture optimization can be accessed when operating the wind farm at constant frequency. The main advantage of CF comparing to VF is the simplicity of the control. In case of variable frequency it is impossible of controlling the speed independently of each wind turbine.

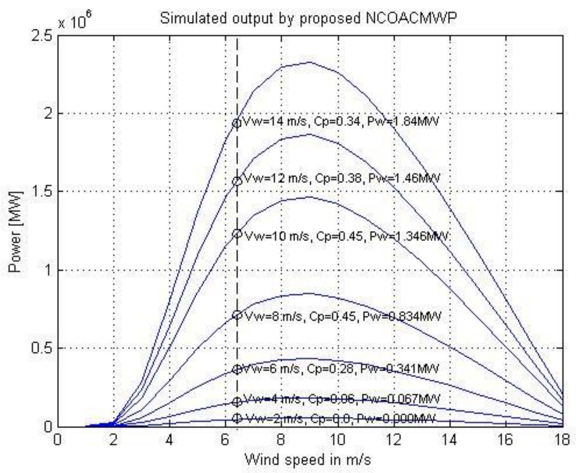

Fig 6. Power Generated by single wind turbine for different Wind speed

A similar strategy can be applied to a whole wind farm. As a whole, the scope of research should be aimed at a maximum power capture that will have less power losses, high efficiency and consequently will be more reliable and less costly during the operation. Losses and reliability analysis and system details of such a configuration will be presented in future publications.

Fig 6 represents the different wind speed scenarios of a single wind turbine which maximizes the power generation for a CF of 50Hz. Similarly for various wind turbines, generated power can be analyzed for a off shore wind farm.

5. Conclusion

The proposed, NCOACMWP algorithm has been successfully applied to 2MW rated single wind turbine. The objective of the work is to capture the maximum power from wind energy, , in that one of the approaches is to have a strong optimization algorithm for the parameters utilized in wind turbine. The proposed NCOACMWP has successfully achieved in the capturing of power from 83.5 % to 94.0% is improved from previous algorithm in literature. Moreover, this paper accessible an appraisal of power generated by constant frequency wind farms connected to a single large power converter.

NCOACMWP technique has been presented, including the analysis of different wind speed cases generated randomly by a Weibull distribution. It has been revealed that a remarkable improvement of capturing wind power of 7.5% obtained. The results put forward a good potential for single wind farms which show more power generation than VF which is the most optimum result. Thus shows the following advantages: lesser cost, minor maintenance requirements which are particularly critical for offshore wind farms, higher consistency due to the lesser number of components which can eventually present problems and lower converter losses.

Future work

In future, the work can be carried out for optimizing other different parameters involves in wind turbine, wind speed of any different wind generators.

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